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Development of new simulation method that considers electricity and heat demand distribution for performance evaluation of residential fuel cells

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ABSTRACT

Targets for carbon dioxide reduction were set in February 2005 under the Kyoto Protocol. Ever since, Japan has strongly focused on reducing emissions in the residential sector. Tokyo Gas Co., Ltd. is focusing on the development and commercialization of residential fuel cell cogeneration systems—a polymer electrolyte fuel cell (PEFC) and a solid oxide fuel cell (SOFC)—which save primary energy and reduce carbon dioxide emissions by utilizing simultaneously produced electricity and heat. To date, we have evaluated the primary energy consumption of fuel cells under specific electrical and heat demands. However, there has been a strong need to develop a new method that considers demand distribution to estimate the potential market for fuel cells. Here we develop a new simulation method by 1) conducting a large-scale questionnaire survey based on more than 10,000 samples to determine the electricity and heat demands as well as 2) calculating the primary energy consumption of fuel cells for the entire range of electricity and heat demands.

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1. Introduction

Ever since targets for carbon dioxide reduction were set in February 2005 under the Kyoto Protocol, Japan has strongly focused on reducing emissions in the residential sector. Emissions reduction in the residential sector is important because it has increased by about 40% as of 2009 compared to 1990 levels and now accounts for 14% of the total carbon dioxide emissions in Japan.

Presently, gas companies in Japan are widely popularizing appliances that save primary energy and reduce carbon dioxide emissions in the residential sector. Tokyo Gas Co., Ltd. is focusing on the development and commercialization of residential fuel cell cogeneration systems—a polymer electrolyte fuel cell (PEFC) and a solid oxide fuel cell (SOFC)—which save primary energy and reduce carbon dioxide emissions by utilizing simultaneously produced electricity and heat. Electricity and heat are generated from chemical reactions between the oxygen from air and the hydrogen produced by reforming natural gas. Fuel cell cogeneration systems have attracted attention as energy-saving appliances in the residential sector because of the higher total energy efficiency compared to large-scale central power stations, which incur a great deal of heat loss.

Tokyo Gas Co., Ltd. has been collaborating with Panasonic Corporation to develop PEFCs. In practice, PEFCs have already been used as residential cogeneration systems (under the brand name ENE FARM) since 2009. Approximately 4,000 units have been sold as of Feb. 2011. Although SOFCs are still in the development phase, we have already started field verification tests.

In aiming to determine the optimal specification and ways to popularize fuel cells, it is important to understand customer usage of electricity and heat, and to evaluate the effects of saving primary energy, carbon dioxide, and running costs, because fuel cells simultaneously generate electricity and heat. Tokyo Gas Co., Ltd. has conducted a number of validation tests on the practical use of PEFCs to survey their effects on saving primary energy [1]. In addition, energy conservation under a specific demand of electricity and heat has been simulated for evaluating PEFC and SOFC performance [2, 3]. To date, however, energy conservation has not been simulated under the entire range of electricity and heat demands; moreover, the distribution of electricity and heat demand has not been determined for current consumers of Tokyo Gas Co., Ltd.

In this paper, we show the results of a large-scale questionnaire survey based on 10,000 samples to characterize the electricity and heat demand distribution. Furthermore, we developed a new simulation method to calculate the potential market size for fuel cells by summing the number of consumers for which the performance saves primary energy and reduces carbon dioxide and running costs for each demand.

2. Overview of residential fuel cells

2.1. Composition

PEFCs and SOFCs have a fuel cell unit to generate electricity and a hot water storage unit to store the generated exhaust heat co-instantaneously. In addition, they have a high-efficiency (95%) back-up boiler (Eco-JOES) in the case that stored hot water is insufficient. Eco-JOES represents an improved efficiency thanks to its ability to recover the latent heat in emissions. The fuel cell unit consists of a desulfurizer, fuel processing system, fuel cell stack, inverter, and so on. The fuel processing system reforms hydrogen from city gas after removing the sulfur from city gas odorants with the desulfurizer. The fuel cell stack generates direct current power by reacting oxygen with the gained hydrogen. The inverter converts direct current to alternative current and supplies it to the residential unit.

2.2. Specifications

Table 1 lists the specifications of the PEFC, ENE FARM, developed by Tokyo Gas Co., Ltd. and Panasonic Corporation and the SOFC developed by Tokyo Gas Co., Ltd. for field verification tests (photographs shown in Fig. 1). Both the PEFC and SOFC have high electrical and heat-recovery efficiencies.

Table 1 Specifications of the PEFC named ENE FARM and the SOFC

	ENE FARM (PEFC)	SOFC
Electrolyte	Proton Exchange Membrane	Oxide (Zirconium oxide)
Charge Carrier	H^+	O^{2-}
Rated Power	1 kW	700 W
Electrical Efficiency	37% (LHV)	42% (LHV)
Heat Recovery Efficiency	52% (LHV)	35% (LHV)
Operation Control	➢ Operates in response to hot water usage ➢ Daily Start and Stop (DSS)	➢ Operates in response to electricity usage ➢ Continuous Operation

Fig. 1 Photographs of the (left) PEFC named ENE FARM and the (right) SOFC

2.3. Operation control

2.3.1. ENE FARM

Table 1 shows that for ENE FARM, the efficiency of exhaust heat recovery is higher than that for electricity. Hence, ENE FARM produces much more heat than electricity. This indicates that the generated heat supply is probably in excess of what is needed in the case that it operates in accordance with the electricity demand. Therefore, we have designed ENE FARM to operate in response to hot water usage. In other words, ENE FARM works only with sufficient heat demand. Fig. 2 shows a simple diagram of ENE FARM operation following hot water usage in a residential unit. It runs when electricity demand occurs while the hot water storage is insufficient, as predicted by the adaptive control system for estimating the peak of daily hot water demand.

2.3.2. SOFC

The SOFC has a higher electrical efficiency than ENE FARM because the high operation temperature can compensate for the lack of heat needed to reform hydrogen from city gas. In contrast, the SOFC cannot operate with frequent starts and stops because it requires much more time owing to the high operation temperature. Thus, the SOFC continuously operates in accord with electricity usage.

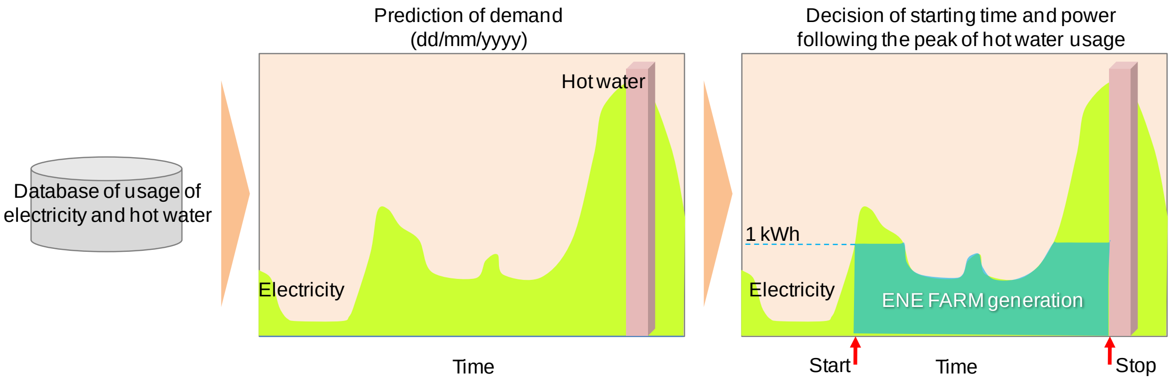


Fig. 2 Diagram explaining the operation control of ENE FARM

3. Development of a new simulation method

3.1. Overview

To date, energy saving in fuel cells has been simulated for a specific electricity and heat demand. However, this is inadequate to evaluate the performance of fuel cells, especially in estimating the potential market size, because the performance pattern and efficiency can change depending on how much demand occurs, as mentioned above.

Therefore, we developed a new simulation method that computes the potential market size for a fuel cell, i.e., the number of consumers that sufficiently benefit by installing it in their homes. The new method consists of three main modules that perform the following operations: (1) determination of electricity and heat demand distribution for present customers of Tokyo Gas Co., Ltd.; (2) performance evaluation of fuel cell cogeneration systems for a demand of 1 kWh/day in terms of primary energy savings, carbon dioxide reduction, and running cost merit; and (3) integrated simulation to calculate the potential market size for fuel cell cogeneration systems by summing the number of consumers for which the performance is advantageous for each demand (Fig. 3). This method is innovative because it is the first attempt to carry out evaluations not only at a single demand but also for the entire range of demands and because it estimates the potential market size for a product.

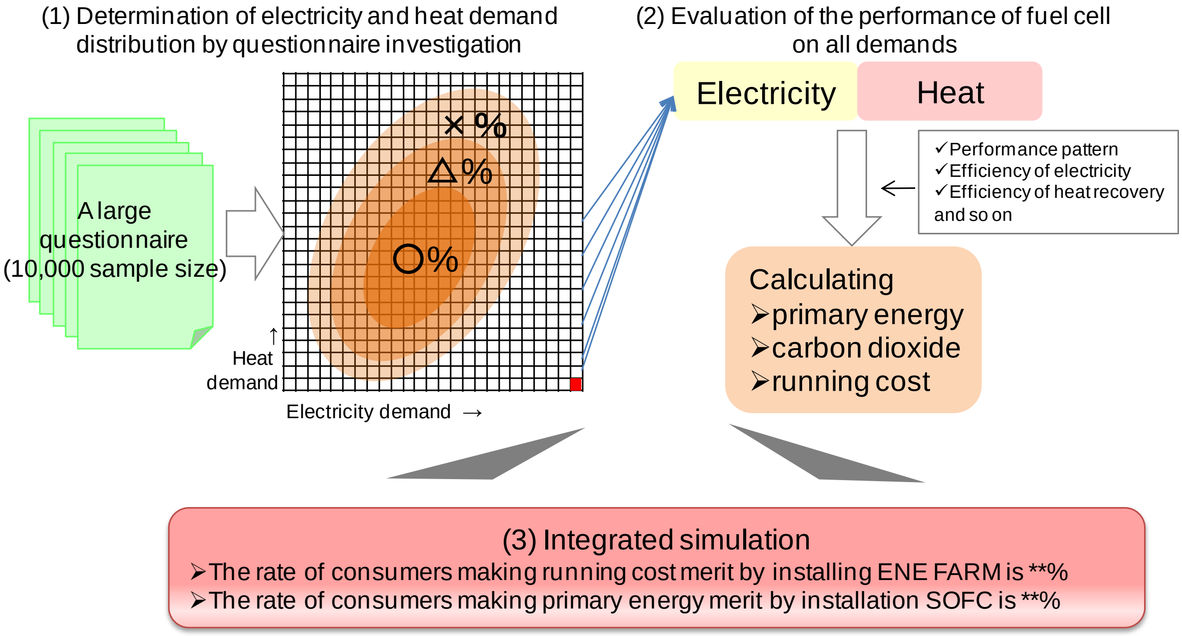


Fig. 3 Schematic of the new simulation method

3.2. Calculation of electricity and heat demand distribution

3.2.1. Outline of questionnaire survey

We conducted a large questionnaire survey (sample size > 10,000) by using the internet in order to determine the electricity and heat demand distribution for consumers living in the service area of Tokyo Gas Co., Ltd. We examined energy consumption in more than 10,000 households by analyzing their gas and electricity bills for twelve months and the appliances consuming the energy. In order to verify accuracy, we selected only households that fulfilled the requirements, i.e., those who stored energy billing statements or kept household accounts. Table 2 shows an outline of the questionnaire survey.

Table 2 Outline of questionnaire survey

Survey period	June 2007
Target group	Tokyo Gas Co., Ltd. consumers living in service area in greater Tokyo
Main items investigated	➢ Gas and electricity bills ➢ Electricity bill plan ➢ Amperage ➢ Household members ➢ Owned appliances ➢ Age of house etc.
Sample size	109,850 samples
Valid sample size	10,265 samples
Screening requirements	➢ Stored monthly billing statements of gas and electricity ➢ Kept household accounts of gas and electricity ➢ Used only city gas (except all-electric homes and homes involving propane gas)

3.2.2. Calculation logic for determining demand distribution

1) Electricity demand

We converted the electricity charges to amounts according to the rate table based on the billing plan and amperage. Furthermore, we directly calculated the household electricity demand Y_1 from the total electricity amount X_1 excluding the demand for space cooling. As for space cooling, we considered the efficiency COP_x of the air conditioning unit according to the manufactured year and the ratio a of the space cooling demand to the total electricity demand.

$$Y_1 = X_1(1-a) + X_1 \cdot a \cdot COPx \qquad (1)$$

2) Heat demand

As in the case of electricity demand, we converted the gas charges to amounts according to the rate table based on the billing plan. Next, we divided the total gas amount into amounts for water heating and cooking by subtracting the cooking amount *C* for each household member *b* only during the summer (selected season with no floor heating demand). Then, we calculated the water heating demand Y_2 by multiplying the water heating amount and the general efficiency of the gas boiler (80%).

$$Y_2 = \left(X_2 - C \cdot b\right) \cdot 0.8 \qquad (2)$$

We estimated the floor heating from the hourly experimental floor heating demand, in addition to time of usage, heat insulation efficiency of the home, and living floor dimensions extracted from the questionnaire. We obtained the heat demand by calculating the water heating and floor heating demands.

As a result, we determined the electricity and heat demand distribution of Tokyo Gas Co., Ltd. consumers in each 1-kWh/day grid.

3.3. Performance simulation

We were able to evaluate ENE FARM, SOFC, and the high-efficiency gas boiler Eco-JOES based on the three criteria of primary energy, carbon dioxide, and running cost under all demands in each 1-kWh/day grid, by simulating their performances and calculating gas and electricity usage. Electricity demand was divided into the three uses of space cooling, heating, and electrical appliances, whereas the gas demand was divided into the three uses of water heating, floor heating, and cooking. Moreover, separate 12-month and 24-hour JIS (Japanese Industrial Standards) demand patterns were plotted for each demand (Fig. 4). We analyzed the energy usage for each appliance through the results simulated for thousands of demands.

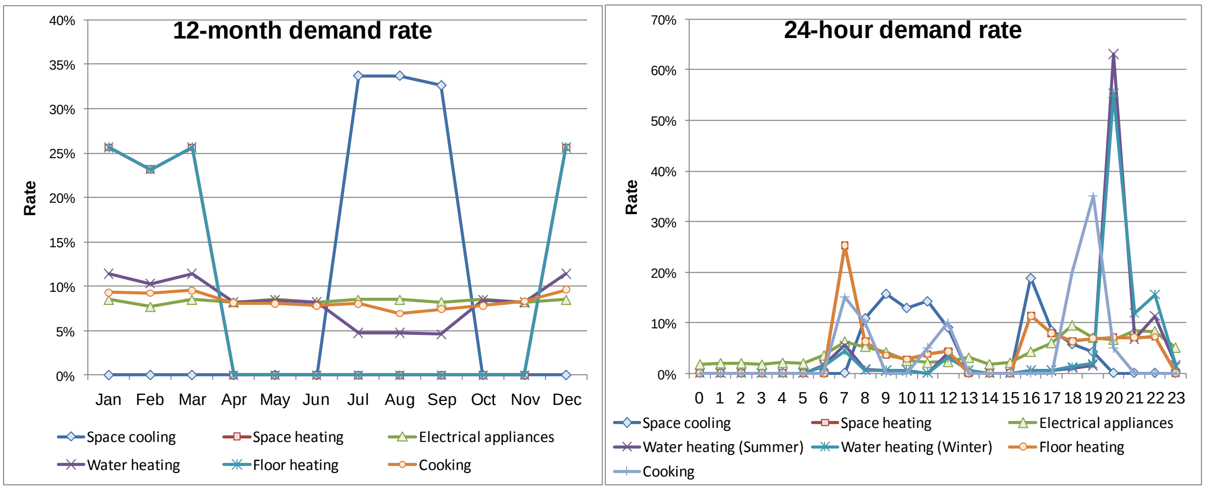


Fig. 4 12-month and 24-hour JIS demand patterns

Fig. 5 shows the energy flows of the fuel cell systems. As mentioned above, ENE FARM operates according to the electricity demand with consideration of the hot water storage capacity predicted by the adaptive control system. In contrast, SOFC operates by considering only the electricity demand. The model we developed is designed to minimize primary energy consumption via intelligent control, by using past data to forecast future demand. We can readily include the tank bulk, heat loss from pipes, partial load efficiency, energy consumption from starting and stopping, and standby electricity as parameters to approximate actual performance precisely.

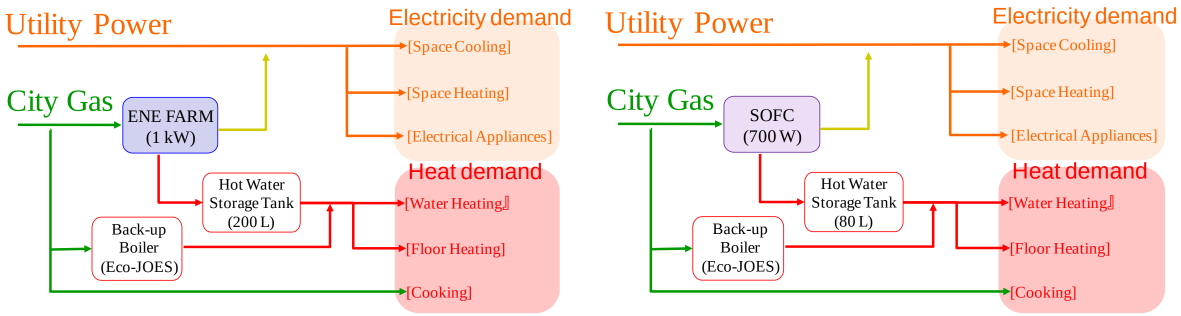


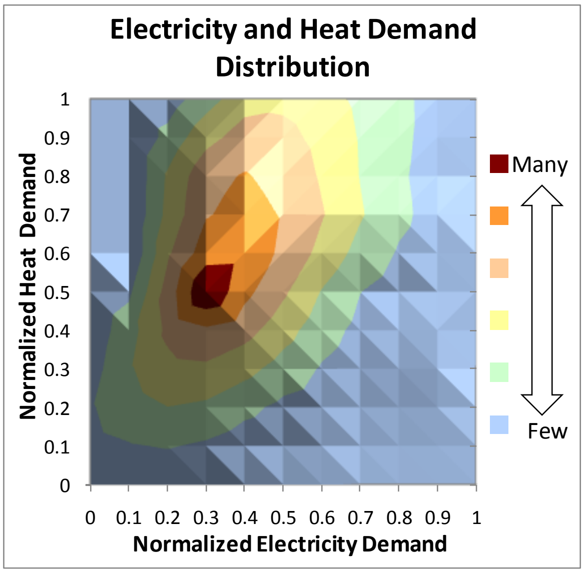
Fig. 5 Energy flows for ENE FARM and the SOFC

3.4. Integrated simulation

By integrating the electricity and heat demand distribution and simulation results, we can estimate the savings for ENE FARM and SOFC as well as the number of existing consumers in each demand area. We calculated the potential market size for a fuel cell by summing the number of consumers.

4. Results

First, an example of the simulated electricity and heat demand distribution is shown in Fig. 6. This figure indicates the number of Tokyo Gas Co., Ltd. consumers that exist in each demand region according to the electricity demand shown on the x-axis and the heat demand shown on the y-axis. The darker the color, the greater is the number of consumers in an area of demand. From the figure, we see that the demand for heat is distributed higher and wider than that for electricity. In addition, this distribution can be divided into several segments according to the sample attribute (e.g., the type of dwelling, household members, area of floor space per dwelling, etc.).

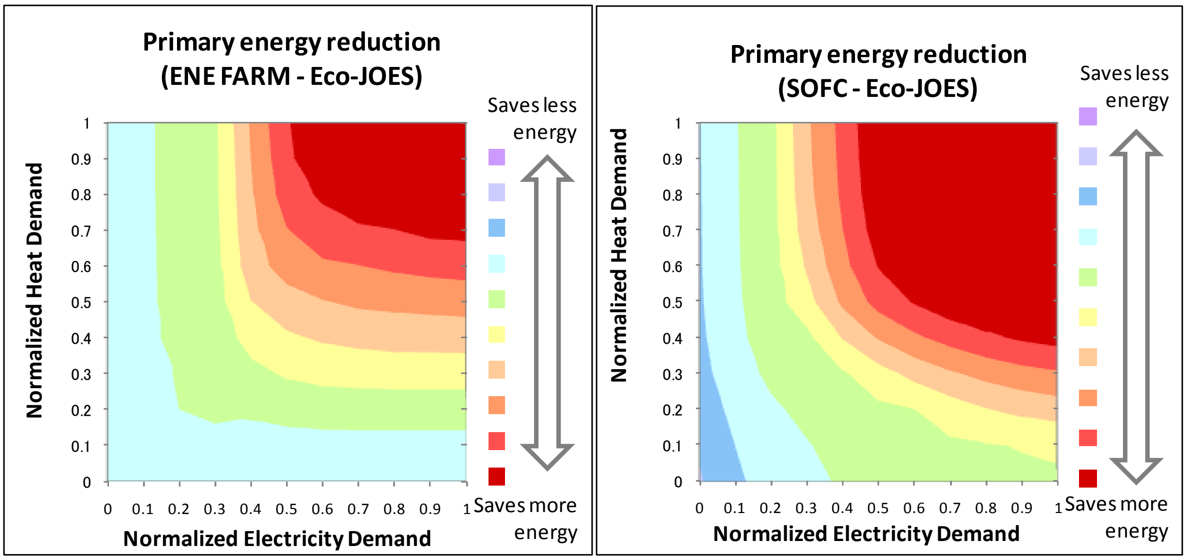


Separate by
- type of dwelling
- household members
- area of floor space
- room layout
- price of household
- income
- Age of house

Fig. 6 Example of electricity and heat demand distribution and possible segmentation by attributes

Second, we present sample results for the performance simulation in Fig. 7, which shows the primary energy savings of ENE FARM and SOFC relative to Eco-JOES as a benchmark. The results clearly show that both ENE FARM and SOFC are superior to Eco-JOES in the region of higher demands for electricity and heat. At the same time, the area of high energy savings for SOFC is greater than that for ENE FARM owing to the higher efficiency of the SOFC. On the other hand, SOFC shows less savings than ENE FARM in the lower demand area because it continues to operate whenever the demand is insufficient (i.e., the partial load efficiency is low).

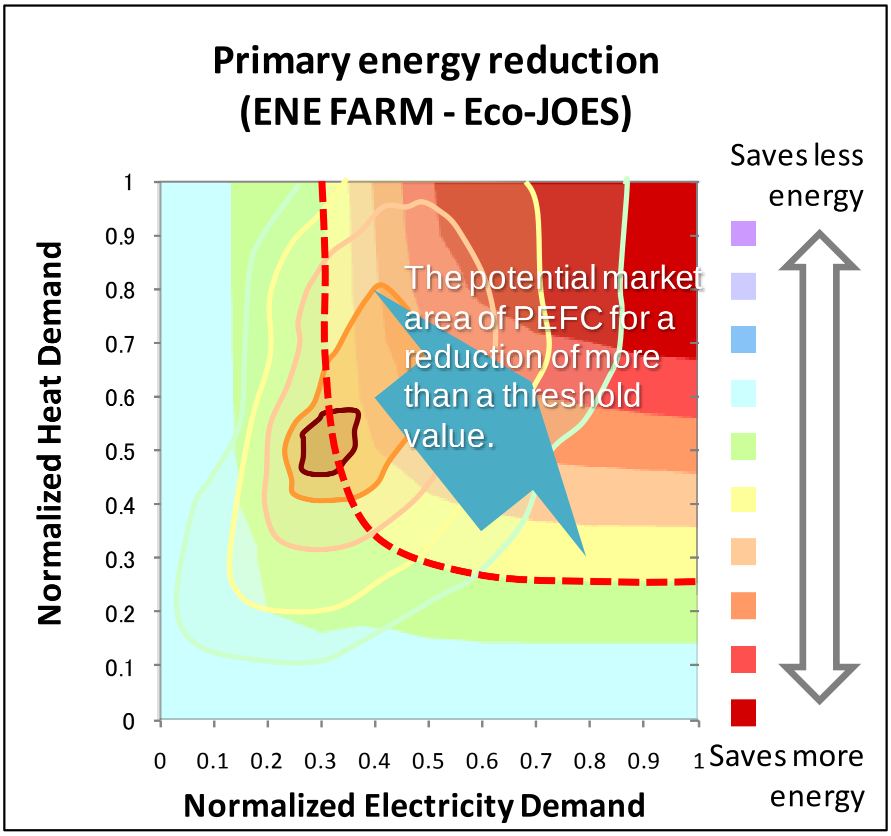
Finally, we determined the potential market size of ENE FARM using the integrated model (Fig. 8). The figure shows the potential market size for reductions greater than a threshold value.



Primary energy reduction (ENE FARM - Eco-JOES)

Primary energy reduction (SOFC - Eco-JOES)

Fig. 7 Map of primary energy reduction of the (left) PEFC and the (right) SOFC compared to Eco-JOES as a benchmark



Primary energy reduction (ENE FARM - Eco-JOES)

The potential market area of PEFC for a reduction of more than a threshold value.

Fig. 8 Potential market of ENE FARM using the integrated model

5. Application of the new simulation method

5.1. Product positioning

By using the integrated simulation, the consideration of optimal product positioning becomes possible. For instance, as shown in Fig. 9, we can set the three gas appliances of ENE FARM, SOFC, and Eco-JOES to the optimal positions based on predictable consumer demands for electricity and heat. The higher the electricity demand, the greater is the advantage of SOFC. In contrast, Eco-JOES is suitable for lower electricity demand, whereas ENE FARM is suited for intermediate demands between SOFC and Eco-JOES.

Product positioning allows us to discuss product strategy, research, and development. In addition, we can compartmentalize several products when they are marketed for the first time. It is also very helpful to specify the target (i.e., the consumer likely to purchase the products), price, place, and promotion strategy because the model includes specific information that indicates how, when, and where consumers consider purchasing a product.

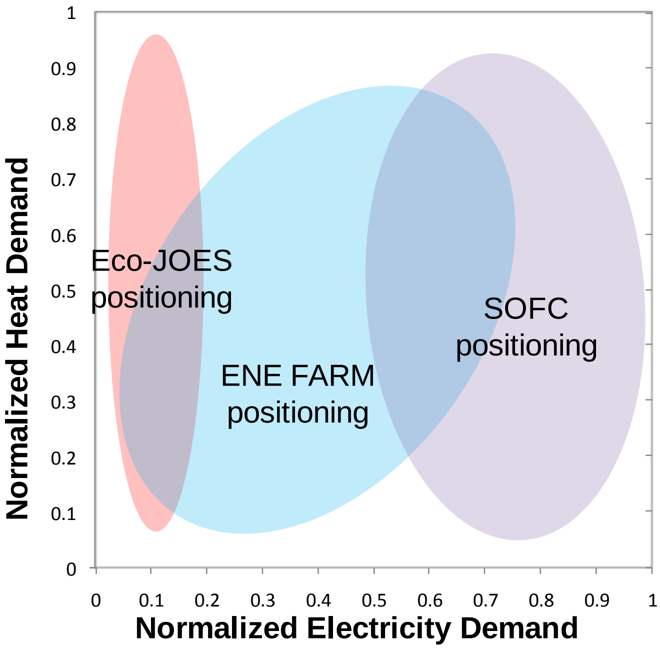


Fig. 9 Diagram of product-positioning map

5.2. Sensitivity analyses of product specification and city gas rate

We can carry out several sensitivity analyses by setting the potential market size as an objective variable with this integrated simulation. For example, it is important to understand the effect of changing the rated power, electrical efficiency of a fuel cell, and the city gas rate on the potential market size.

Specifically, ENE FARM tends to be advantageous at high demands and to stop operating at low demands by increasing the rated power. On the other hand, it often performs and tends to offer advantages at low demands by decreasing the rated power. To determine the optimal rated power, an index of the potential market size can serve as a useful decision-making tool. As in the case of rated power, there is a tradeoff relationship between the efficiency improvement and cost increases for electrical efficiency. The potential market area that shows the biggest cost advantage can help to determine the setting of electrical efficiency. As for designing the rate table of a fuel cell, a consideration of the profit margin multiplied by the potential market size is required.

6. Conclusion

This paper describes the development of a new simulation method to determine the potential market size for fuel cells by analyzing the electricity and heat demand distribution through a large-scale questionnaire survey conducted with customers of Tokyo Gas Co., Ltd., as well as by simulating performance for the entire range of demands. Furthermore, we demonstrate the broad applicability of this simulation to highlight its potential as a market-changing simulation for consideration of product positioning and other strategies.

In the near future, we will upgrade this simulation method to evaluate of other gas appliances as well as future appliances involving electrical equipment. In addition, integrated systems such as smart homes and grids will be focal points for this method in the future.

7. References

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8. List Tables

9. List of Figures